Improving the Effectiveness of Communication Headsets with Active Noise Reduction: Influence of Control Structure

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ABSTRACT

For communication headsets equipped with active noise reduction (ANR), the performance of the control system may influence the communication signal reaching the ear. Conversely, the communication signal may perturb the operation of the ANR system. The interaction between the communication and control signals depends primarily on the control structure, and on the bandwidths and frequency responses of the signal channels. The effects are described for two circumaural communication headsets with similar passive, and active, noise reductions, one with an analog feedback control system and the other an adaptive digital feed-forward control system. Measurements were conducted in a diffuse sound field, with the headsets mounted on a head and torso simulator. The frequency response of sound reproduced by the communication channel was measured when the ANR system was not operating, and when the control system was operating, with swept pure-tones, and broadband noise. The speech intelligibility was estimated for environmental noise shaped to represent the spectrum of speech, the noise within a tank, or the noise within an aircraft cockpit, by the Speech Transmission Index (STI). The STI and fidelity of sound reproduced by the communication channel of the device with a feed-forward control structure tended to exceed that of the more common feedback control structure. This appeared to be a consequence of the compromised frequency response of the earphone and drive electronics employed in the feedback control system to maintain stability of the feedback loop, as well as the presence of communication sounds sensed by the control microphone that were fed back into the controller. The lack of corruption of the communication signal by the feed-forward control system, together with the possibility of using electro-acoustic components with flat frequency responses, suggests that this control structure may be more consistent with the audio fidelity requirements of advanced auditory communication systems.

1.0 INTRODUCTION

A primary expectation of communication headsets is to maintain speech intelligibility and, for advanced auditory communication systems, audio fidelity, under all operational conditions. This is particularly important in circumstances in which degraded auditory communications may have life-threatening consequences, e.g., military operations, and air-traffic control. The requirement may be difficult to maintain in noisy environments and for persons with hearing loss, and also when the communication system is operated at sound levels sufficient to induce temporary threshold shift in the user.

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The technology of active noise reduction (ANR) has been applied to communication headsets for more than two decades, and has achieved success in reducing environmental noise at frequencies below 1 kHz. While the contributions of ANR to improved speech intelligibility and pure-tone signal detection have been well documented [1-7], the simultaneous requirements for effective ANR, improved speech intelligibility and advanced auditory communications, such as spatialized auditory displays, have received little attention.

The purpose of this paper is to explore the interaction between the performance of the control system and sound reproduction by the communication channel in ANR headsets, with particular reference to the control structure. The intention is to identify factors that may suggest new directions for improving the audio effectiveness of future headsets, hearing protectors, helmets or earplugs equipped with ANR. The discussion is centered on the performance of two circumaural hearing protectors equipped with active noise control systems and a communication channel, one with a feedback control structure and the other with a feed-forward control structure.

2.0 APPARATUS AND METHODS

The metrics employed were the physical measurement of ANR, and the frequency response and Speech Transmission Index (STI) of the communication channel and its associated electronics. The apparatus and methods are summarized in the following sub-sections.

2.1 Test Room

A reverberation room was used for this study. The rectangular room was designed in accordance with the requirements of ISO 3741 (1975), with dimensions of 6.1 m (length) x 4 m (width) x 5 m (height). The room has an estimated diffuse-field low-frequency cut-off of 110 Hz. Four multi-element loudspeaker systems, positioned near the corners of the room at floor level, provided a broadband source of environmental noise (55 Hz to 8 kHz), and could produce an A-weighted sound level of up to about 100 dB.

2.2 Noise Reduction

The passive, and active, noise reductions of the two headsets were measured when the devices were mounted on a manikin (Bruel & Kjaer Head and Torso Simulator, HATS). The built-in microphone within the right ear simulator of HATS was used to record the sound pressures. The measurements of noise reduction were conducted using band-limited white noise with an A-weighted sound level of ~90 dB.

2.3 Frequency Response of Communication Channel

The frequency responses of the earphones in the two headsets and their associated drive electronics were obtained when the headsets were mounted on HATS with cushions sealed, first when the active control system was not operating and then when it was operating. The electronic drive signals were a swept pure tone, or broadband noise, of various amplitudes, which were fed into the input of the communication channel. The sound output of the earphone was monitored by the microphone within the ear simulator of HATS.

2.4 Speech Transmission Index

The influence of ANR on speech intelligibility was estimated using the STI, which is a figure of merit for a communication link that varies from zero (no intelligibility) to unity (perfect intelligibility) [8]. The STI

signal was fed into the input of the communication channel, and its amplitude was adjusted to produce an A-weighted sound level at the ear of 70 dB.

The environmental noise spectrum at the center-head position (i.e., in the absence of HATS) was shaped to approximate the long-term average of speech, or to correspond to the noise spectrum inside a Leopard tank, or in the cockpit of a Buccaneer aircraft. The noise spectrum of the Leopard tank is dominated by low frequency components between 100 and 500 Hz. In contrast, the noise spectrum in the cockpit of the Buccaneer aircraft is broadband, with sound pressure levels increasing with increasing frequency to above 5 kHz. For each environmental noise spectrum, the A-weighted sound level at the microphone of the ear simulator of HATS was adjusted to produce a prescribed speech signal-to-noise (S/N) ratio. In order to focus the results on the active performance of the headsets, the measurements were performed with the A-weighted sound level of the noise under the earmuff adjusted to be 67.5 dB when the ANR systems were not operating. This procedure adjusts for differences in the passive attenuation of the two headsets [9]. The "speech" S/N ratio was then 2.5 dB, and resulted in the speech-spectrum shaped environmental noise producing an A-weighted sound level of close to 90 dB at the center-head position.

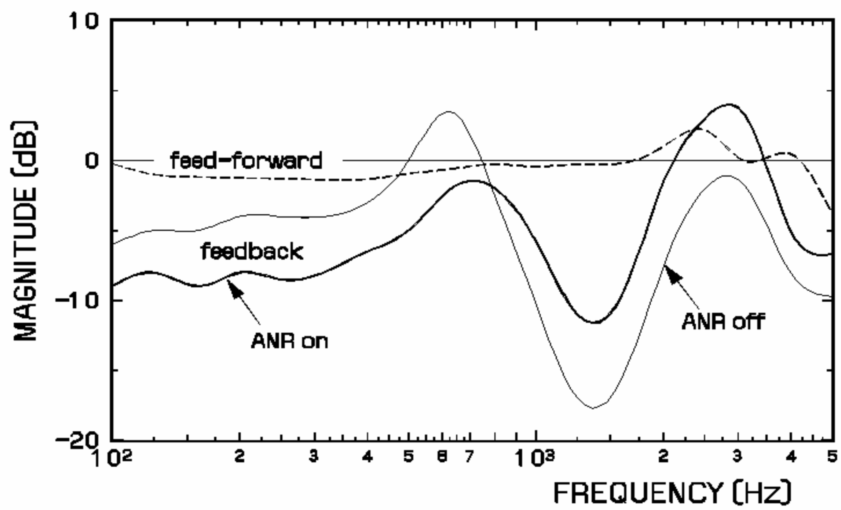

Figure 1: Frequency response of sound reproduced by communication channel of headsets with feedback ANR control system (ANR "off", and "on"), and feed-forward control system.

3.0 RESULTS

The frequency responses of the sound reproduction system in the headset with feedback control are shown in Fig. 1 when the control system was operating (curve "ANR on") and not operating ("ANR off"). As can be seen from the diagram, the frequency response of the earphone and its associated electronics in this headset displayed large frequency-dependent variations in amplitude. It should be noted that the earphone and associated electronics selected for a feedback control system is a compromise between satisfying the need for maintaining stability of the feedback loop and for communication fidelity. In contrast, the frequency response of the sound reproduction system in the headset with feed-forward control possessed little dependence on

frequency from 100 to 5000 Hz, except for a small peak (~2-3 dB) from 2 to 3 kHz (dashed line in Fig. 1). The response did not change when the control system was operating.

Table 1: STI for Headset with Adaptive Feed-forward, or Fixed Filter Feedback Control System

	Speech Spectrum	Leopard Tank	Buccaneer Cockpit
Feed-forward, ANR - ON	0.64	0.77	0.62
Feedback, ANR - ON	0.57	0.77	0.58
Feed-forward, ANR - OFF	0.64	0.77	0.62
Feedback, ANR – OFF	0.43	0.73	0.50

As already noted, the A-weighted sound level of the environmental noise at the artificial ear was set to be the same for both headsets when the control systems were not operating. This was to accommodate differences in the passive noise reductions between the headsets of up to ±5 db at some frequencies, and hence focus the STI measurements on the active performance of the devices. The headsets thus operated with the same "speech" S/N ratio under this condition. The ANR of the two headsets were comparable in magnitude and frequency range (~12-15 dB at frequencies below 200 Hz, falling to near zero by 300-400 Hz) [9]. The STIs of the two headsets are shown in Table 1 for the selected environmental noise spectra. It can be seen from the Table that the STI of the headset with the feed-forward control system tended to be greater than that for the headset with the feedback control system, except for the noise source dominated by low frequencies (Leopard tank). The STI recorded for the headset with feed-forward control was not affected by whether the control system was operating, or not operating, suggesting that the ANR was contributing little to the improvement of speech intelligibility in this device. This was not surprising, as the control system had been optimized to reduce low-frequency helicopter noise, including noise at the rotor fundamental blade-passage frequency (16 Hz), and not to improve speech intelligibility. The STI recorded for the headset with feedback control increased substantially when the control system was operating, but never exceeded the STI recorded by the headset with feed-forward control.

4.0 DISCUSSION

Communication signals have been introduced into the control loop of an analog fixed-filter feedback active noise control system in a number of ways [10]. An effective method has been described by Steeneken et al. [11], and is shown in the simplified block diagram of Fig. 2A. In this diagram, the control signal paths are shown by continuous lines, and the communication signal paths by dashed lines. The control filter is designed to operate in such a way as to cancel the sound sensed by the microphone E, which provides its input signal. An essential part of this process is the transformation of the electrical signal from the control filter into sound by the earphone, S, the propagation of sound from S to the microphone, E, and the transformation of sound into an electrical signal by the microphone. These transfer functions together define the error path: in this terminology, microphone E is the error microphone and its output is the error signal. The error path in many

ways governs the performance of the control system. For example, the error path transfer function will define the magnitude and frequency range of ANR: also, the error path is influenced by the presence of an air leak around the cushion sealing the earmuff to the side of the head, and an active noise control system can become unstable if this function changes sufficiently.

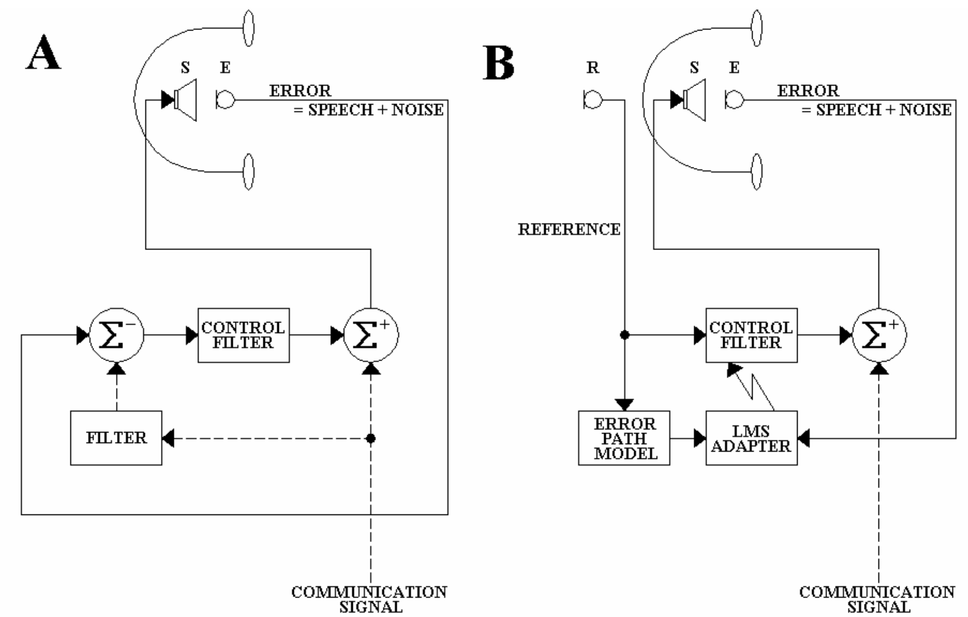

Figure 2: Communication headset with ANR and: A – feedback, or B – feed-forward control structure. For description, see text.

An important consequence of a feedback control structure is that the error signal contains both residual environmental noise and speech from the communication channel, which are fed back into the input of the control filter (Fig. 2A). As the role of the control filter is to attempt to null the error signal, this will have the effect of cancelling the communication signal as well. To mitigate this undesirable effect of the control structure, Steeneken et al. introduced an additional filter to enable the communication signal to be subtracted from the error signal prior to entering the control filter (see dashed lines in Fig. 2A). The success of this addition to the basic control structure may be judged by inspecting the results in Table 1 and Fig. 1. It is evident from Table 1 that the STI for the headset with the feedback control structure, which employed a variant of the method illustrated in Fig. 2A, is less for environmental noise spectra containing substantial components at speech frequencies above 500 Hz when the control system was not operating (e.g., results for speech-spectrum shaped noise, and Buccaneer noise). Under these conditions, the "speech" S/N is low in frequency bands contributing substantially to the STI, and no reduction in environmental noise or corruption of the speech signal by the control system is occurring. In these circumstances, the STI reflects the fidelity of the sound reproduction system in the headset with the feedback control system in comparison to that of the headset with the feed-forward control system. That the frequency response of sound reproduction by the

feedback control system is less than ideal is shown by the dashed curve in Fig. 1. As already noted, the earphone and drive electronics employed in the feedback ANR control system must satisfy the need for maintaining stability of the feedback loop, and so commonly compromise the magnitude response in order to obtain the necessary phase response and hence group delay through the system. Both the magnitude of the frequency response and the STI improve when the control system is operating (solid line, Fig.1, and Table 1, respectively), reflecting the combined effect of ANR, frequency-dependent amplification of the communication signal, and subtraction of a filtered version of the communication signal from the error signal. While the improvement in speech intelligibility anticipated from the increase in STI is encouraging, it is not clear that this control structure will produce adequate audio fidelity for advanced auditory communication systems involving, for example, spatial auditory displays. The provision of two earphones in one earmuff – one for ANR, and the other for sound reproduction – may, however, improve audio fidelity.

The basic control structure for an adaptive feed-forward active control system applied to a communication headset is shown by the continuous lines in Fig. 2B. The control structure employs an additional microphone, R, the reference microphone, that is external to the earmuff and provides the input signal to the control filter. In this control structure, the control filter must model the propagation of the environmental noise from R to E, as well as taking into account the electro-acoustic transfer function of the earphone, the propagation of sound from S to E, and the acousto-electric transfer function of microphone R. This process is implemented by successively adjusting the transfer function of the control filter to optimize the ANR, and is usually performed digitally by an adaptive filter (indicated by the curled arrow in the diagram). The adjustment involves minimizing the squared magnitude of the instantaneous error signal, and was performed by the normalized filtered-X least mean squares (LMS) algorithm in the device employed for this study [12]. Convergence to the "best" performance of the adaptive filter and the stability of the control system are assured by pre-filtering the reference signal prior to calculating the update of filter coefficients by a model of the error path. Details of the hardware and software needed to achieve broadband ANR in the small dimensions of a circumaural headset have been described elsewhere [13].

In this control structure, the communication signal is simply added to the output of the control filter (dashed lines in Fig. 2B). Note that the error signal, while still consisting of the residual noise and speech, does not become the input to the control filter and so cannot perturb the communication signal. As can be seen from Fig. 2B, the presence of the residual speech in the error signal may perturb the convergence of the filtered-X LMS algorithm resulting in less than optimum ANR, as the error signal is used to update the filter coefficients. The influence of changes in the error path, such as occur when the headset is re-fitted to the head or worn by different individuals, may be accommodated by determining person-specific error path transfer functions and in this way rendered less likely to destabilize the adaptive control system [14]. While a possible reduction in the ANR from maladjustment of the adaptive control filter cannot be excluded, inspection of the results in Table 1 indicates that the magnitude of any change in ANR is not sufficient to render the STI of the headset equipped with the feed-forward control system less than that of the feedback system in circumstances in which the ANR may be expected to contribute to the intelligibility, namely in environmental noise dominated by low-frequencies (e.g., Leopard tank). Moreover, the lack of corruption of the communication signal by the control system, together with the absence of the need for the earphone and drive electronics to possess responses tailored to maintain the stability of a feedback control loop, permits the use of electro-acoustic components with flat frequency responses. Thus, a feed-forward control structure appears to be consistent with the audio fidelity needed for advanced auditory communication systems to be built into headsets, hearing protectors, helmets, or earplugs equipped with ANR.

5.0 CONCLUSIONS

For headsets with effectively equalized passive, and similar active, noise reductions, the STI and fidelity of sound reproduced by the communication channel of a headset with a feed-forward ANR control system tended to exceed that of a headset with the more common feedback ANR control system.

The earphone and drive electronics employed by the feedback control system possessed a compromised magnitude response most probably to obtain the necessary phase response and hence group delay through the system, to satisfy the stability requirements of the feedback loop. Both the magnitude of the frequency response and the STI improved when the control system was operating, reflecting the combined effect of ANR, the subtraction of the communication signal from the error signal, and frequency-dependent amplification of the communication signal. The lack of corruption of the communication signal by the feed-forward control system, together with the absence of the need for the earphone and drive electronics to possess responses tailored to maintain the stability of a control loop, permitted the use of electro-acoustic components with flat frequency responses. A feed-forward control structure would thus appear to be more consistent with the audio fidelity needed for advanced auditory communication systems.

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